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Impurity transport in collisionless trapped-particle-driven turbulence

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Context: gyrokinetic simulations of impurity transport in the core of tokamaks

Fusion efficiency is sensitive to core impurity concentration

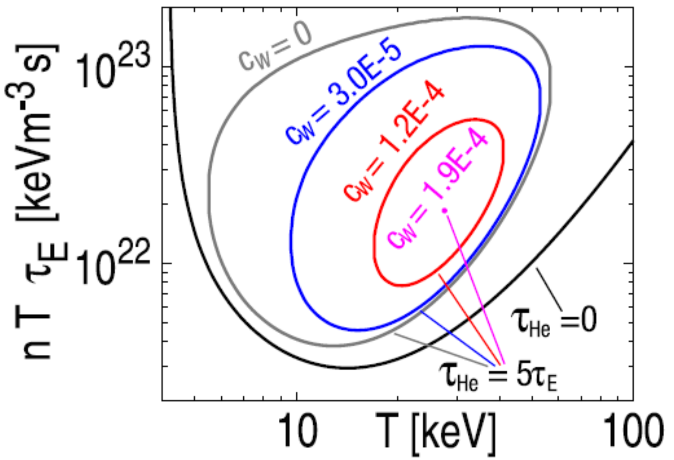
- Reduction of tungsten concentration from 1.2×10^{-4} to 0.3×10^{-4}

  40% decrease in required triple product

  40% decrease in required temperature

  $\Rightarrow$ easier access to ignition

[Pütterich NF'10]



Challenge for gyrokinetic simulations

- Neoclassical and turbulent transport [Romanelli NF'98]
- Synergistic coupling [Estève NF'18]
- Disparate timescales

Focus on dynamics of trapped particles

$\Rightarrow$ **bounce-averaged gyrokinetics**

Objectives: Qualitative impacts of impurity concentration, charge, mass, and gradients

1. Impact of concentration

- In general, turbulence $\rightleftarrows$ impurities $\Longrightarrow$ self-consistent (active) treatment
- But if concentration $\rightarrow$ 0, passive treatment is a promising approach. **Limit of validity? Smooth transition or critical threshold?**

2. Diffusion, thermo-diffusion, and curvature pinch

- Total density flux of impurity with charge Z

$$\Gamma_z = -D_z[\nabla n_z + C_T \nabla T_z + C_P \nabla q]$$

Diffusion Thermodiffusion Curvature

- Each contribution can be isolated by varying the density and temperature gradients, and by artificially switching on/off the curvature drift

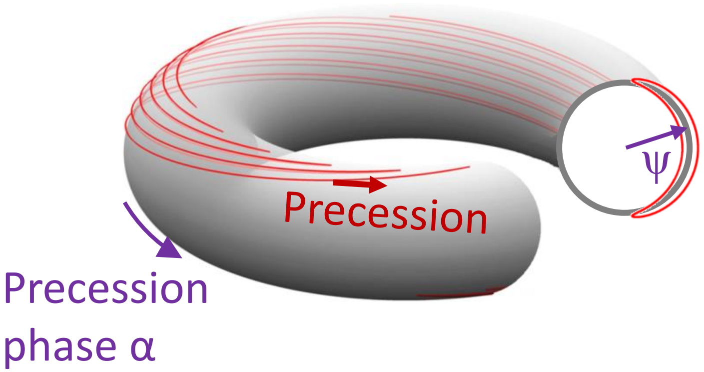
$\Rightarrow$ **parameter scans in charge, mass, gradients, and magnetic shear**

Reduced model for trapped-particle-driven turbulence

[Depret PPCF'00]
[Sarazin PPCF'05]

Bounce-averaged gyrokinetic model

- Based on frequency ordering for TIM and TEM
  $\omega \sim \omega_{precession} << \omega_{bounce} << \omega_{cyclotron}$
- Kinetics of trapped particles only
  (adiabatic passing particles)
- 2D phase space (angle α, radius ψ)
  + 2 parameters (energy and pitch-angle)



$$\frac{\partial f_s}{\partial t} + [J_0\phi, f_s]_{\alpha,\psi} + \omega_{d,s}\frac{\partial f_s}{\partial \alpha} = 0 \qquad \omega_{d,s} = E\Omega_d/Z_s$$

$$\underbrace{C_{ad}\left(\phi - \epsilon_\phi\langle\phi\rangle\right)}_{\delta\rho_{passing}} - \underbrace{C_{pol}\sum_s C_s\tau_s Z_s^2\bar{\Delta}_s\phi}_{\delta\rho_{polarization}} = \frac{2}{\sqrt{\pi}}\sum_s \underbrace{\left(Z_s C_s\int_0^\infty J_{0,s} f_s E^{1/2}\mathrm{d}E\right)}_{\delta\rho_{trapped}}$$

$\Rightarrow$ **TERESA simulation code (N species)**

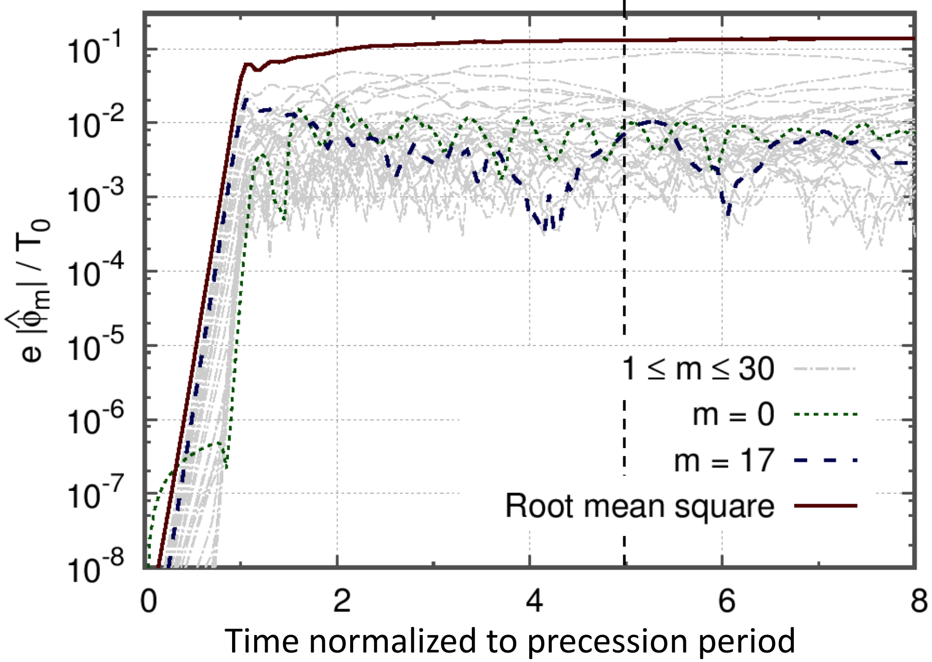
[Drouot EPJD'14]
[Cartier-Michaud JPCS'15]

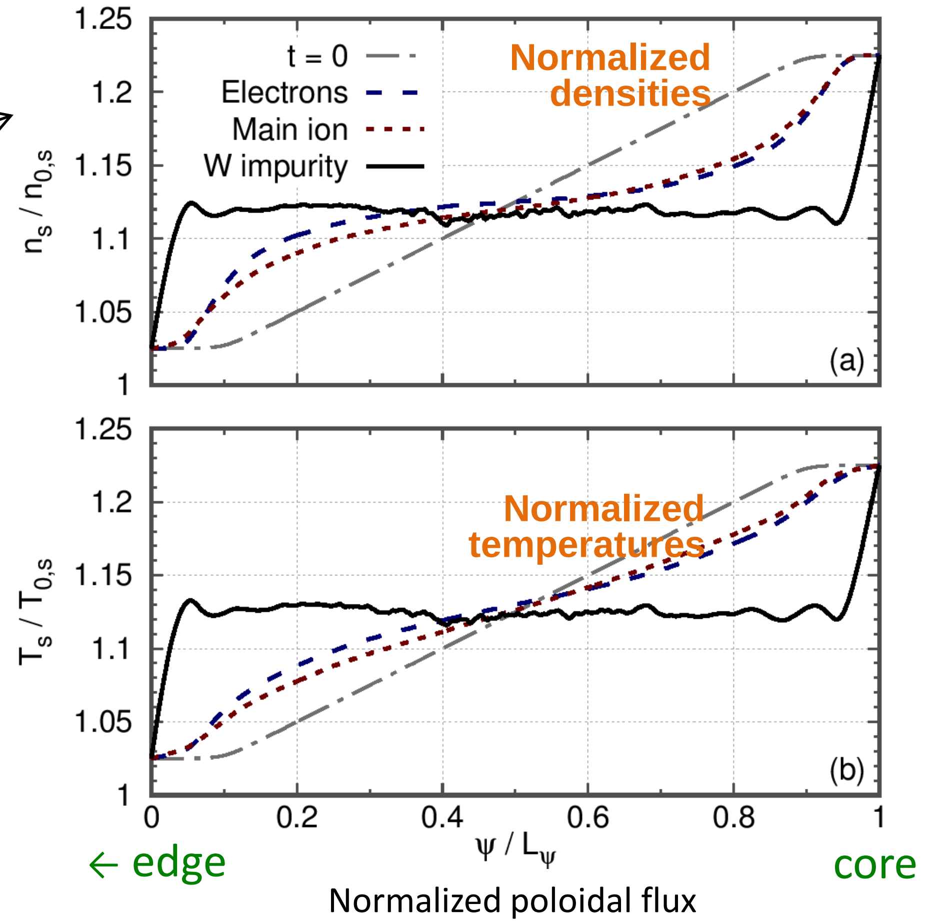
1. Impact of impurity concentration

Timescale of flattening of impurity profiles depends on concentration

Typical simulation with low tungsten concentration $C_W=10^{-5}$

- Initial gradient lengths $L_n = L_T \approx a/4$

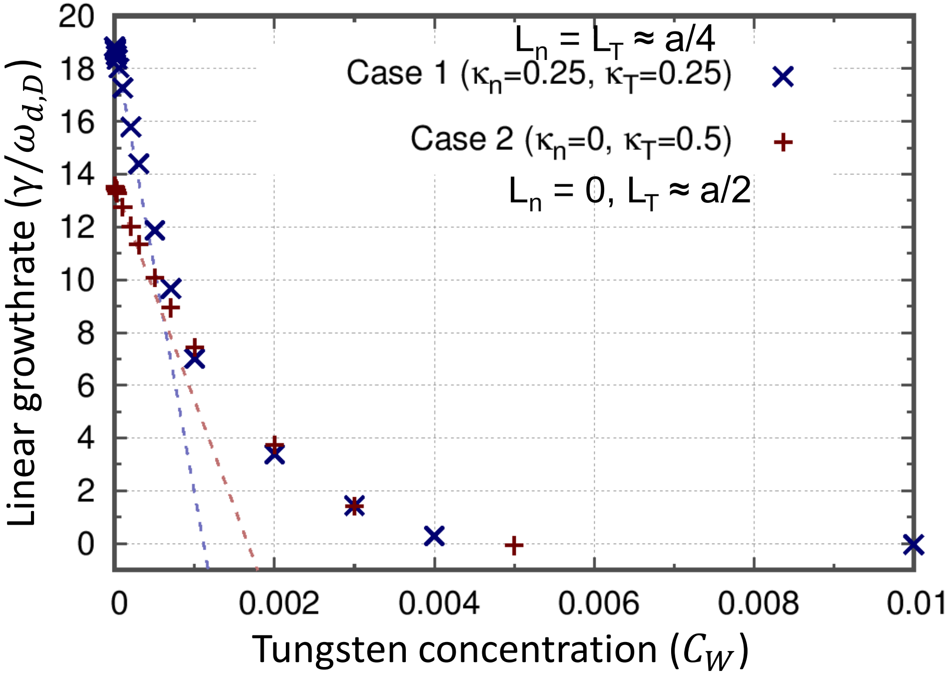




Timescale of flattening or impurity profiles

- Trace concentration → within a fraction of a precession period
- Non-trace concentration → several precession periods (similar to main species)

Growth rate and turbulence intensity decrease with increasing C_W, linear for $C_W < 5.10^{-4}$

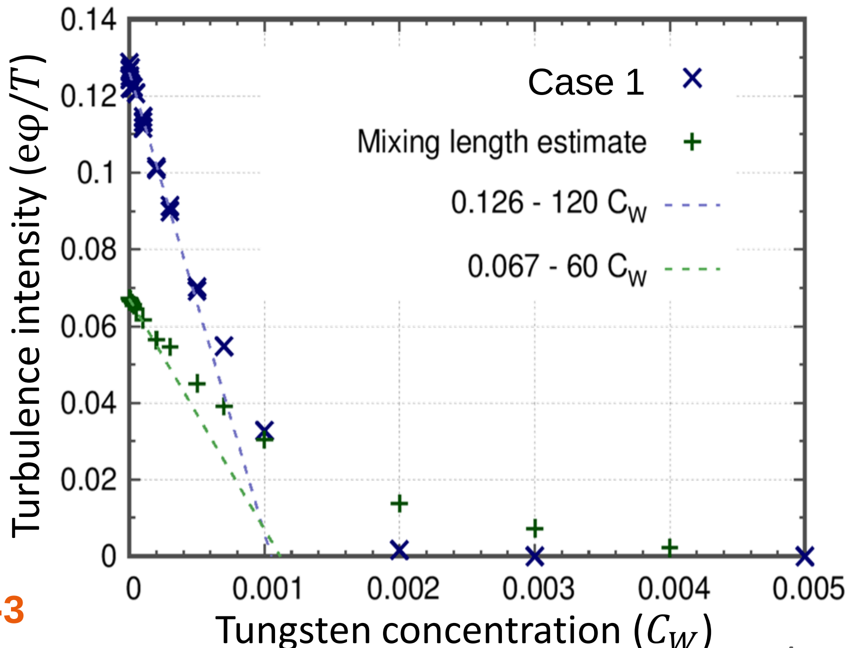


Linear growth rate ↓ with C_W ↑

- Consistent with linear GK [Dominguez NF'89] [Du NF'14]
- Due to dilution
- $\frac{\gamma - \gamma_0}{\omega_{d,D}} \sim -10^4\, C_W$
- Quantitative agreement with analytic theory [Lesur NF'20]

Turbulence intensity ↓ with C_W ↑

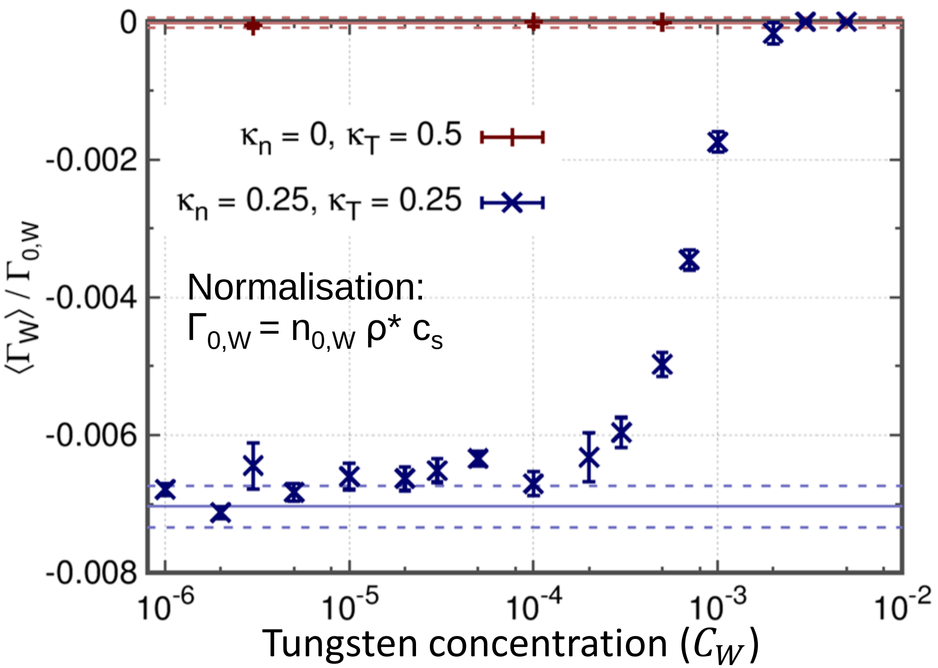
- Qualitative agreement with mixing length estimate $e\phi/T_0 = \gamma/(k_r \rho_{c,i} k_\theta c_s)$
- But not simply proportional to γ



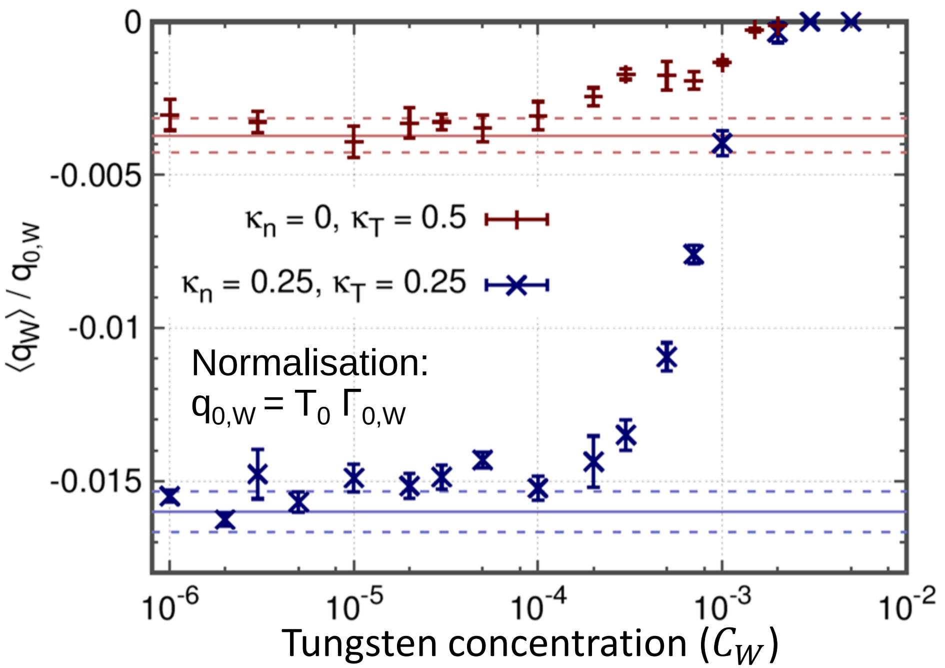
⇒ Passive treatment valid for $C_W \ll 10^{-3}$

C_W=2.10^{-4} threshold for radial fluxes of W^{40+}

Radial density flux



Radial heat flux

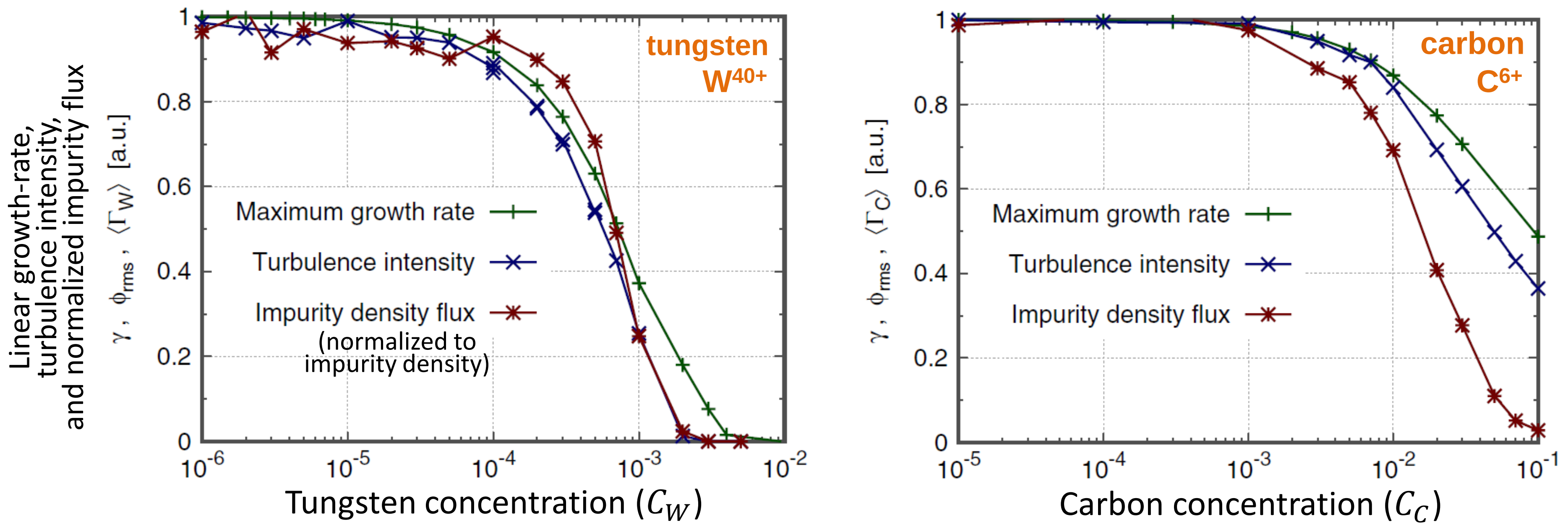


Caveats

- Effect of low-frequency turbulence only, no neoclassical transport
- Small system size ($\rho^* \approx 1 / 30$), radial profiles constrained by thermal baths

Comparing the effects on linear modes, turbulence, and transport

Dependency of normalized impurity transport is more threshold-like than that of linear growth rate and turbulent intensity



- Here, all quantities are normalized to their value in the limit of zero impurity concentration

Transport quenching is due to phase synchronization

[Lesur NF'20]

- Electric potential fluctuations synchronize to impurity density fluctuations
- Occurs only above critical concentration

2. Diffusion, thermo-diffusion, and curvature pinch

Impact of charge and mass numbers on diffusive impurity transport

$$\Gamma_z = -\boldsymbol{D_z}[\boldsymbol{\nabla n_z} + C_T \nabla T_z + C_P \nabla q]$$

Isolating particle diffusion

- Flat impurity temperature profile
- Curvature drift artificially switched off

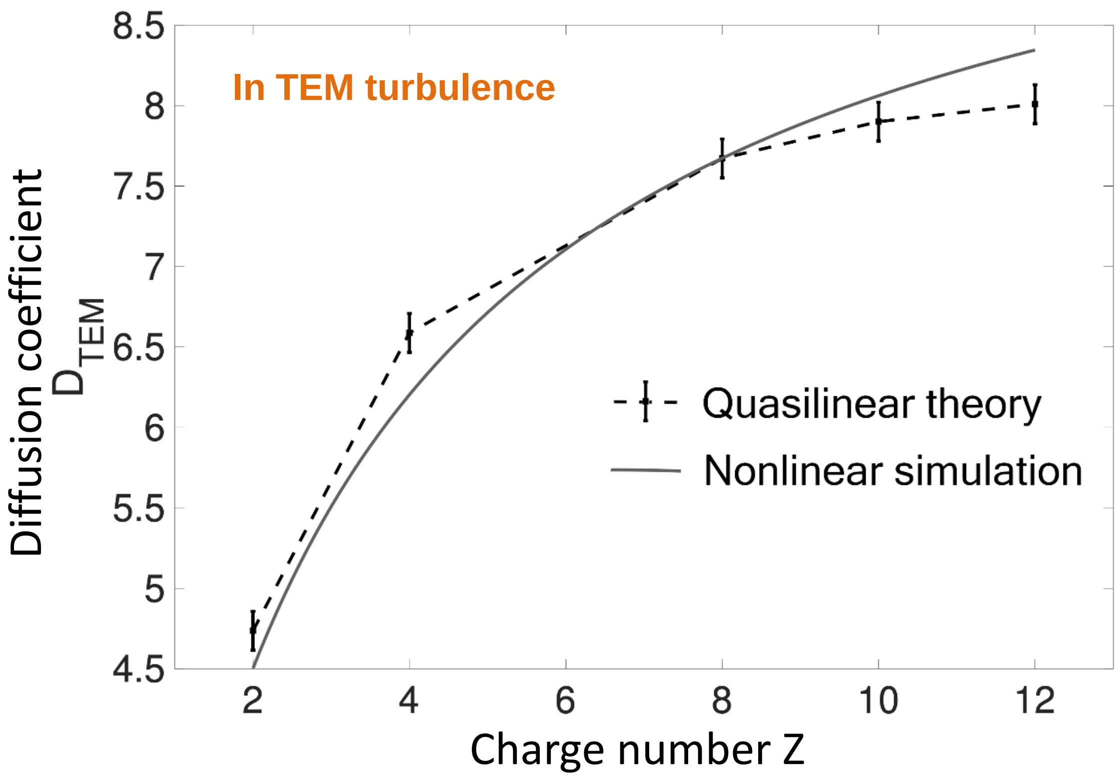
Scan in mass (A) and charge (Z) of impurities

- Dependency depends on the nature of dominant instabilities :

  TEM → Diffusion ↑ as Z ↑

  TIM → Diffusion ↓ as Z ↑

- Weak dependency on A (diffusion ↓ slightly as A ↑)



[Gravier PoP'19]

- Qualitative agreement with quasi-linear theory

Thermo-diffusion brings impurities inwards in TEM turbulence, but outwards for TIM

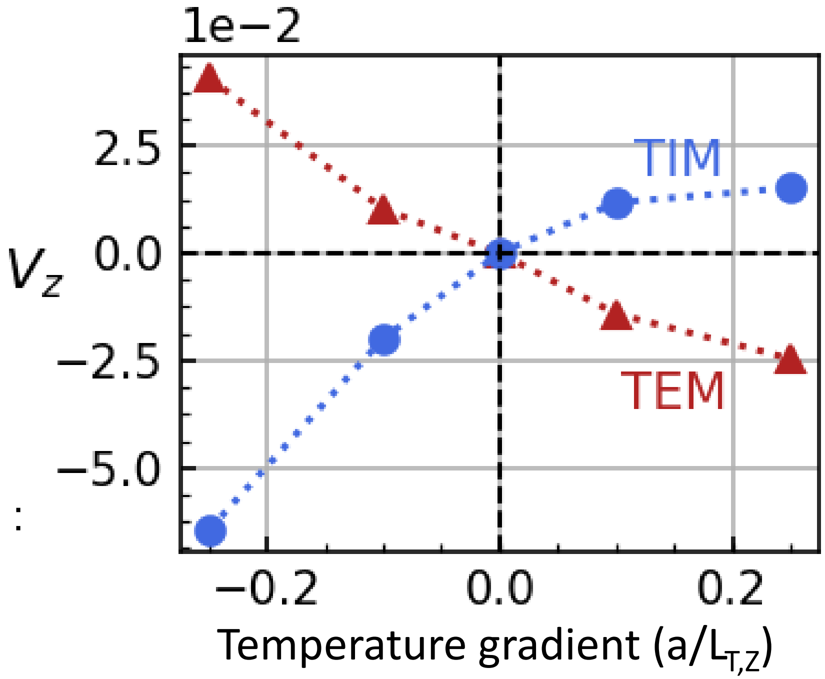
Isolating thermo-diffusion

$$\Gamma_z = -D_z[\nabla n_z + \boldsymbol{C_T \nabla T_z} + \cancel{C_P \nabla q}]$$
$$= -D_z \nabla n_z + n_z V_z$$

- Curvature drift artificially switched off
- Impossible to maintain flat impurity density gradient

  ⇒ impurity density gradient such that $\Gamma_z = 0$, then $V_z = D_z \frac{\nabla n_z}{n_z}$

  (D_z: obtained from density scan)



[Lim PPCF'20]

Scan in temperature gradient

- For standard sign of impurity temperature gradient, thermodiffusion transport impurities :

  TEM → inwards

  TIM → outwards

Scan in charge number

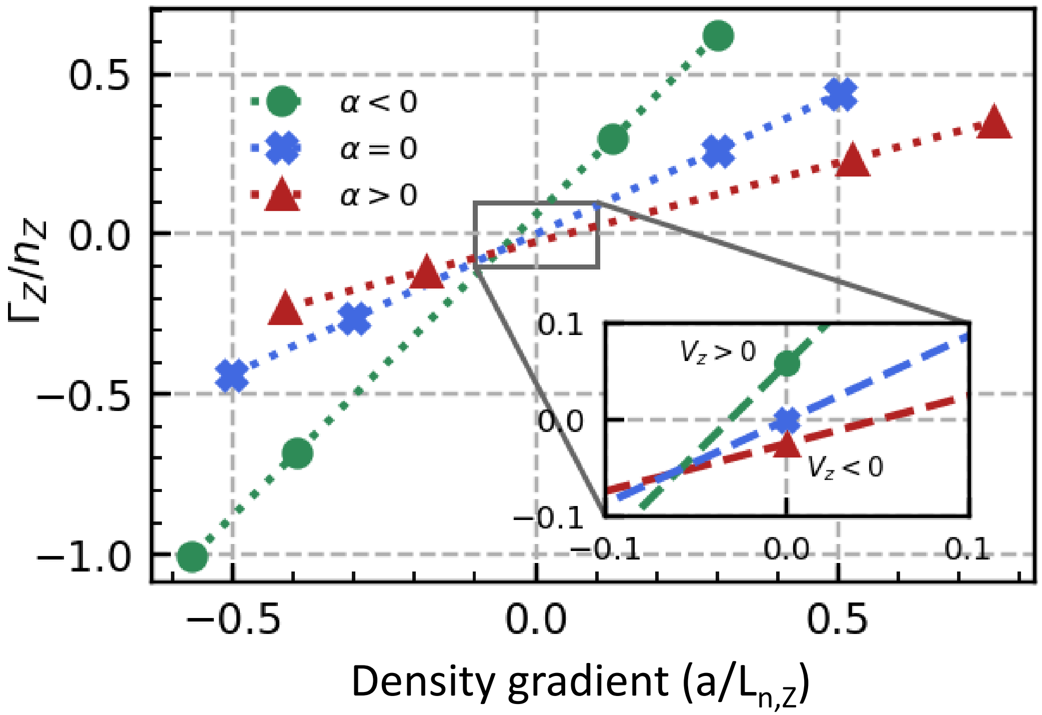
- The coefficient C_T ↓ as Z ↑

Curvature pinch is inward except for reversed magnetic shear

$$\Gamma_z = -D_z[\nabla n_z + C_T \nabla T_z + \boldsymbol{C_P \nabla q}]$$

Isolating curvature pinch

- Flat impurity temperature profile
- Focus near zero impurity density gradient



Role of magnetic shear

- Reversed magnetic shear can change the sign of precession frequency
- Artificial coefficient α in front of $\omega_{d,Z}$ to model this effect

Scan in density gradient

- Curvature pinch is inward except for reversed magnetic shear

[Lim PPCF'20]

Summary

Scan in impurity concentration

- TEM growth rate and turbulence intensity decrease with increasing tungsten concentration, linearly for concentrations below 5.10^{-4}
- For turbulent transport of W^{40+}, passive treatment valid for $C_W<2.10^{-4}$

Parametric dependencies of impurity transport

$$\Gamma_z = -D_z[\nabla n_z + C_T \nabla T_z + C_P \nabla q]$$

Increases (decreases) with increasing Z for TEM (TIM)

Thermodiffusion:

TEM $\rightarrow$ inwards

TIM $\rightarrow$ outwards

$C_T \downarrow$ as Z $\uparrow$

Curvature pinch: inward except for reversed magnetic shear

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